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POLYMETAMORPHIC HISTORY OF THE CRIXÁS-AÇU GNEISS, CENTRAL BRAZIL: SHRIMP U–PB EVIDENCE FROM TITANITE AND ZIRCON

CLÁUDIA LIMA QUEIROZ[1, 2], NEIL J. MCNAUGHTON[2], I. R. FLETCHER[2], HARDY JOST[1] AND MARK E. BARLEY[2]

ABSTRACT A sample of the Crixás-Açu gneiss in Central Brazil contains protolith and metamorphic zircons, and two generations of metamorphic titanite. SHRIMP U-Pb data of these different mineral generations indicate the following temporal sequence: tonalitic magmatism at 2817 ± 9 M.y derived from an older source region (3050 to 2930 M.y zircon cores); Archaean metamorphism at 2772 ± 6 M.y (from zircon) with cooling to the blocking temperature of titanite (at 2711 ± 34 Ma); followed by Palaeoproterozoic metamorphism and weak fabric development at 2011 ± 15 Ma, and a possible Neoproterozoic metamorphism. The field relations and these age data indicate the polymetamorphic history of the area and demonstrate the value of in situ age determinations on well-characterized rocks.

Keywords: Archean, Central Brazil, gneiss complexes, geochronology, titanite, SHRIMP

INTRODUCTION In the past decade, precise U–Pb geochronological techniques have markedly improved tectonic studies in greenstone belts, including SHRIMP analyses of zircons and other accessory minerals such as titanite. Zircon ages have generally been used to determine the crystallization ages of the rocks and the ages of inherited components, whereas titanite ages are commonly used to determine the ages of rocks or metamorphic events. Using SHRIMP analyses of titanite and zircon from a single sample of Crixás-Açu Gneiss, we have been able to resolve multiple metamorphic events in the history of the Caiamar Complex.

GEOLOGICAL SETTING The study area is a part of the Archaean terranes of the Tocantins Province (Almeida 1967, Fig. 1), central Brazil. It consists of low-grade greenstone belts and granite-gneiss complexes in a typical M-type dome-and-keel structure (*sensu* Marshak *et al*. 1997). Supracrustal rocks occur in three elongate, NS-trending belts named from West to East, the Crixás, Guarinos and Pilar de Goiás (Fig. 1). The Archaean block is partially overthrusted by Proterozoic metasedimentary sequences. Previous Sm–Nd, Rb–Sr, Ar/Ar, Pb/Pb, and U–Pb data (Tassinari and Montalvão 1980, Montalvão 1986, Arndt *et al*. 1989, Vargas 1992, Jost *et al*. 1993, Pulz 1995,

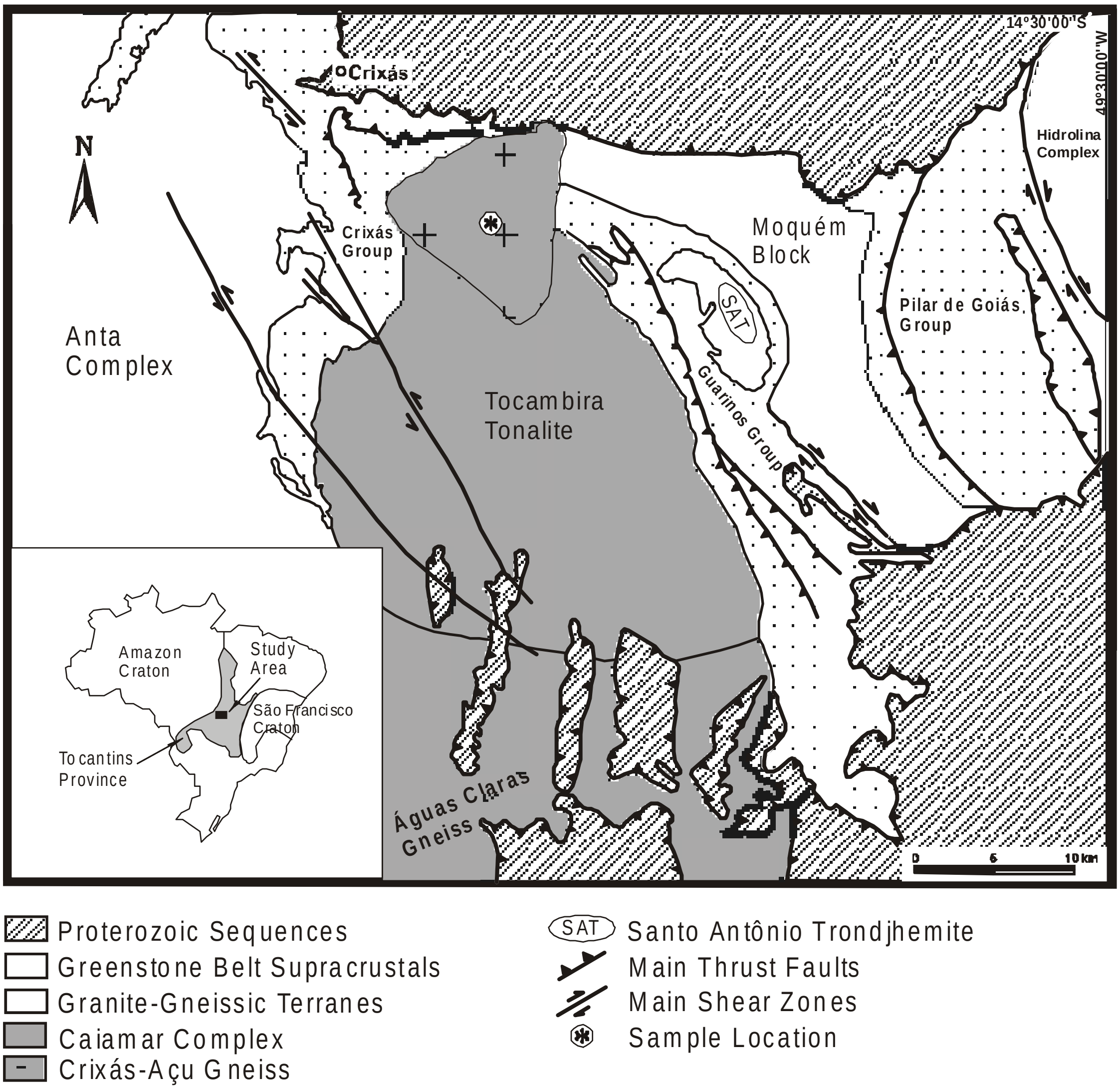

Figure 1. Simplified geologic map of the Crixás Granite-Greenstone Belt Terrane.

1 – Instituto de Geociências, Universidade de Brasília, Brasília, 70.910-900, Brazil
2 – Center for Strategic Mineral Deposits, Department of Geology and Geophysics, University of Western Australia, Nedlands, WA 6907, Australia

Fortes *et al*. 1997) suggest that the region developed under three main tectonic stages: (i) basin stage, including deformation and metamorphism of greenstone belts, followed by granitoid magmatism (3.0 Ga to 2.4 Ga); (ii) intrusion of basic dyke swarms and a dioritic intrusion (ca. 2.1 Ga); and (iii) overprinting during the Brasiliano/Pan-African Cycle (750 to 500 Ma).

A wide variety of textural, structural and compositional Archaean granitoids occur in the area. The Caiamar Block (Danni and Ribeiro 1978) was mapped in detail and renamed by Jost *et al*. (1994) as a Complex, which contains three major units: the Crixás-Açu and Águas-Claras Gneisses, and the Tocambira Tonalite which intrudes both gneisses (Fig. 1). The Complex also contains minor mafic dykes, pegmatoid veins, and migmatites.

The typical Crixás-Açu Gneiss is light gray, fine to medium-grained, and has a metamorphic compositional banding given by the alternation of millimeter- to meter-wide melanocratic bands, and millimeter- to centimeter-wide leucocratic bands, both with granoblastic to lepidoblastic texture. The melanocratic bands have a tonalitic composition, and their major minerals are saussuritized oligoclase and quartz, with subordinate biotite and, locally, hornblende. Hornblende is commonly transformed into biotite and titanite. Zircon, apatite, epidote, titanite, muscovite, and locally microcline are accessory, whereas chlorite, sericite, and clinozoisite are secondary. The leucocratic bands are trondhjemitic and made up of albite and quartz, with minor biotite and zircon, and locally secondary carbonate. The gneissic banding is commonly overprinted by a faint crosscutting foliation given by the orientation of biotite and muscovite. Titanite and zircon are commonly intergrown with quartz and plagioclase, but the former also occurs in association with biotite of the overprinted faint foliation.

About 25 kg of the Crixás-Açu Gneiss was collected for U–Pb geochronology (see location in Fig. 1). The heavy-minerals concentrate was prepared at the University of Brasília, and further processed at the University of Western Australia following the procedures outlined by Smith *et al.* (1998). Representative zircon and titanite crystals were hand picked and mounted in epoxy (UWA mounts 98-38 and 98-77, respectively) with chips of the CZ3 zircon and Khan titanite standards.

Zircon occurs in three morphological types. Type 1 consists of very clear, prismatic and commonly bipyramidal, euhedral to subhedral crystals. The grains are typically about 150 mm long, with a length/width ratio of about 3:1. Fractures and inclusions occur but are uncommon. Optical zoning and internal structure are not visible under transmitted or reflected light, but charge-induced contrast images (Griffin 1997), show finely zoned euhedral rims and diffuse cores.

Type 2 crystals are usually clear, pale to light brown, prismatic and bipyramidal, euhedral to subhedral. The crystals are between 90 mm and 300 mm long and have a length:width ratio of 2.5:1 to 3.5:1. Fractures are quite common and there are rare inclusions. Zoning is visible under transmitted and reflected light, and, as in Type 1, Charge contrast images show diffuse cores with euhedral rims. Except for the darker color, which may reflect higher radiation damage, and zoning that is visible under transmitted and reflected light, Types 2 and 1 are similar.

Type 3 is rare and differs from the other types in several features. The crystals are transparent, prismatic, euhedral to subhedral, usually broken and much clearer than those of Type 1. The lengths of the unbroken crystals range between 80 mm and 180 mm, and their length/width ratios are between 2:1 and 3:1. The crystals lack fractures, inclusions, and zoning under transmitted and reflected light microscope, as well as in most of the Charge contrast images, but in rare cases show a Maltese Cross-type zoning.

Titanite is in general very clear, light brown and consists of fragments of larger grains. The fragments have many internal fractures and fluid inclusions, and lack zoning under transmitted and reflected light or in backscatter electron images.

ZIRCON U-Pb GEOCHRONOLOGY

The SHRIMP data from zircon crystals were obtained during two sessions, following the methods described by Smith *et al*. (1998). The 1s reproducibility of the Pb/U ratio of the CZ3 standard was ± 1.48% (n = 13) and ± 0.69% (n = 10) in the two sessions. A total of 29 analyses were performed on 15 crystals. The amount of common Pb, measured by ^{204}Pb, was almost insignificant and similar to that of the standard, and it is assumed to derive from the gold coating and surface contamination. The Pb isotope composition of Broken Hill galena was used to correct for the common Pb.

A concordia diagram (Fig. 2) shows the majority of data to be discordant. Concordant to nearly-concordant data (above 95% of concordance) show an age range from ca. 2.77 Ga to 3.05 Ga. One apparent cluster of four analyses (types 1 and 2, including three core and 1 rim analysis) has a pooled age of 2817 ± 9 M.y (95% confidence limit; Group 1). One Type 3 zircon, with a typical annealed, metamorphic morphology, yielded two analyses (Group 2) with indistinguishable ages averaging 2772 ± 3 M.y (95% confidence limit) but two other analyses on the same grain gave discordant older and younger ages.

TITANITE U-Pb GEOCHRONOLOGY

Neumayr *et al.* (1998) describe the method of data acquisition for titanite. The data were taken during two sessions, with a 1s reproducibility of the Pb/U ratio of the Khan standard of ±1.10% (n = 8) and ±1.15% (n = 8). Twenty-six grains were analyzed, totaling 31 determinations. The amount of common Pb, measured as ^{204}Pb, was low but larger than that of the standard and taken to be an initial Pb component of the grains. The Pb isotope composition of Cumming & Richards (1975) at the age of each analysis was used to correct for common Pb. A concordia diagram (Fig. 2) shows that the majority of the data are concordant. There is a distinct, major data population at 2011 ± 15 Ma (^{207}Pb/^{206}Pb age, 95% confidence limit, c^2= 0.69, n = 19, Group 2), with another possible cluster at 2711 ± 34 Ma (95% confidence limit, c^2= 0.17, n = 3, Group 1).

DISCUSSION

The oldest near-concordant zircon analyses from grain cores yield ages from 3050 Ma to 2930 Ma. These are interpreted as inherited cores rimmed by magmatic zircon. The spread of core ages may reflect multiple sources or partial resetting of old zircon. The ^{207}Pb/^{206}Pb ages show no correlation with ^{232}Th/^{238}U and Th/U cannot be used to distinguish different zircon populations. The 2817 ± 9 Ma age of the youngest four concordant to nearly-concordant data of Types 1 and 2 zircon is interpreted as the age of the tonalitic magmatism. The *ca*. 2772 Ma Type 3 zircon suggests that the pluton underwent metamorphism about 45 Ma after the intrusion, resulting in a rare partial annealing of zircon grains and age resetting.

The data of most zircon rims are discordant and have high U-contents correlated with younger ^{207}Pb/^{206}Pb ages. Additionally, the discordant data with ^{207}Pb/^{206}Pb ages older than 2750 Ma form a linear array trending towards a possible Brasiliano/Pan-African resetting (Fig. 2). However, due to the correlation between the U-content and apparent age, it is uncertain to interpret the discordant array as due to a Neoproterozoic event or to a Pb loss by diffusion.

The titanite data cluster in three different, concordant to nearly-concordant sets in the concordia diagram (Fig. 2), i.e., at *ca*. 2711 Ma, *ca*. 2011 M.y and a spread of from 2680 Ma to 2607 Ma. These data may be interpreted in many ways. First, does the 2011 M.y titanite age represent a resetting of the 2711 M.y population and, consequently, the spread of data from 2680-M.y to 2607-M.y represents a diffusive Pb-loss chord? Or, on the other hand, do the 2711 M.y and the 2011 M.y ages represent two different titanite generations/growth stages?

The absence of morphological differences between both populations, the concordant spread about 2.6 Ga, and the Th/U ratios and U-Th contents of the younger population that varies within the range of the oldest population suggest differential resetting of the oldest population (*ca*. 2711 Ma). However, the absolute lack of data between 2600 Ma and 2237 Ma suggests there is no real Pb-loss chord and that the Th/U ratios may represent only the Th and U contents available in the rock.

There is also the possibility that small parts of the *ca*. 2711 Ma relict grains, could be annealed by the *ca*. 2011 Ma event, a process suggested by Zhang and Schärer (1996), Pidgeon *et al*. (1996), and Cliff and Cohen (1980). Although the titanite population was investigated by backscatter electron images, no distinct cores or foreign fragments were found.

The closure temperature of titanite, defined as the temperature of the system at the time given by its apparent age (Dodson 1973), is assumed to be over 500°C (Cherniak 1993, Mezger *et al*. 1993, Mezger *et al*. 1991, Cliff and Cohen 1980, p.ex.). Titanite grains of approximately 1cm size have closure temperature above 630°C, and of

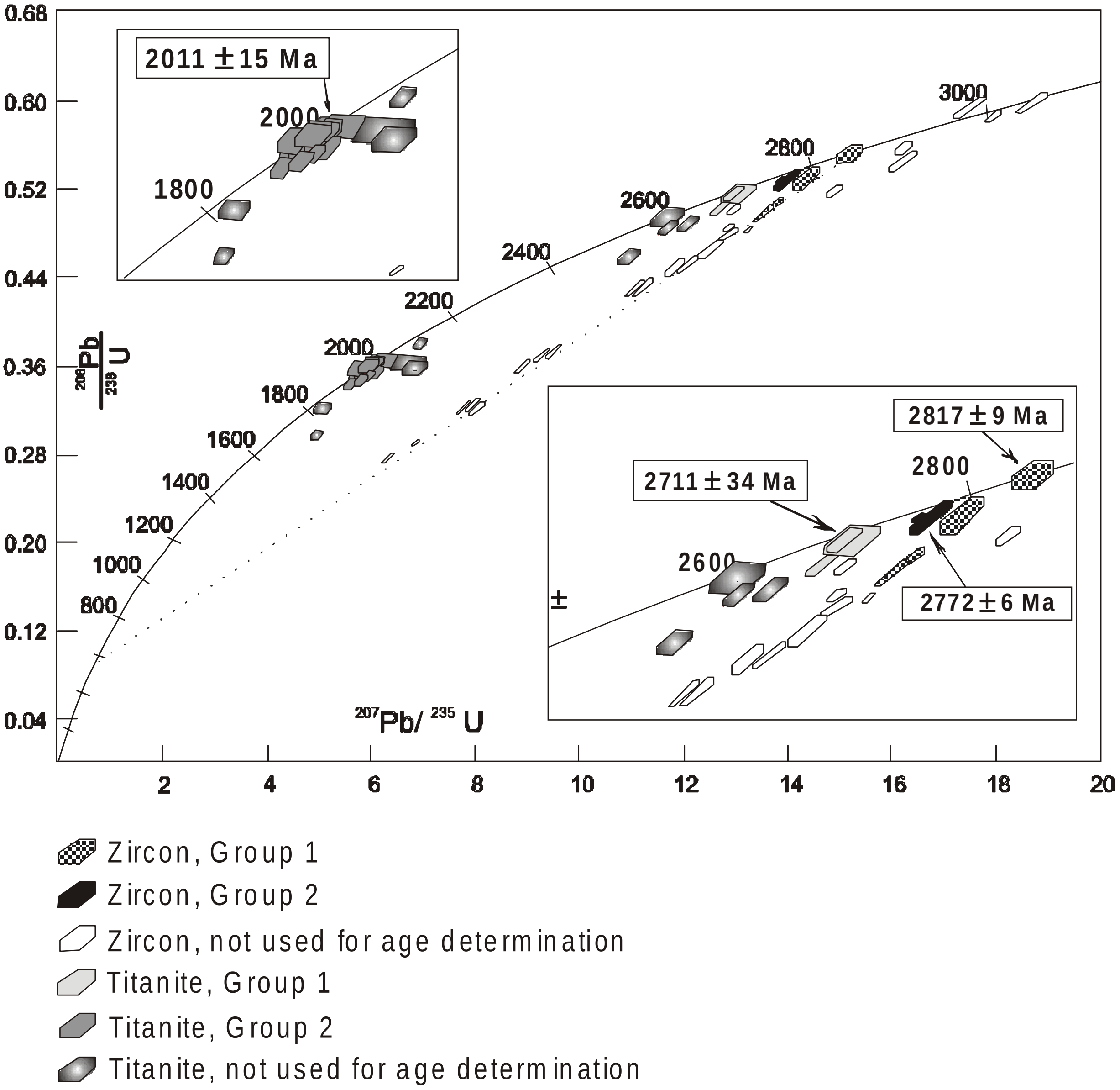

Figure 2. Concordia plot of zircon and titanite data for the Crixás-Açu Gneiss. Error boxes are 68% confidence level, ages are 95% confidence level.

0.05 cm grain-size it is between 500°C and 550°C (Mezger *et al.* 1991, 1993). Cherniak (1993) points out that cores of 0.5 cm titanite crystals have a minimum closure temperature of 780°C, that drops to 650°C in 0.005 cm crystals. There seems to be a consensus that smaller grains have a lower closure temperature.

The studied titanite grains are fragments of crystals between 0.005 cm and 0.01cm, compatible to a minimum closure temperature of 500°C. If the two generations differ in grain-size, then they might have different closure temperatures. However, from thin section examination, the coarser titanite is intergrown with quartz and plagioclase and may be magmatic or metamorphic and formed during the gneissic banding, whereas the smaller titanite is in association with the later biotite-rich crosscutting fabric. Thus, it is suggested that the older population (*ca.* 2711 Ma) formed under higher closure temperature than the younger one (*ca.* 2011 Ma), and the Palaeoproterozoic metamorphism did not completely reset the former. However, the absence of a range of titanite ages between 2.7 and 2.0 Ga, reflecting different grain sizes, would argue against this interpretation. The alternative is that the new growth of 2.0 Ga titanite occurred below the » 500°C blocking temperature of the 2.77-Ga titanite, allowing the earlier titanite to preserve its age. Thus, the zircon age of 2772 ± 6 Ma is interpreted as the age of an Archaean metamorphism whereas the titanite age of 2711 ± 34 Ma is considered as due to further metamorphic cooling. Therefore, the titanite with an age of 2011 ± 15 M.y is interpreted as representing a Palaeoproterozoic metamorphism and deformation.

CONCLUSIONS The U-Pb SHRIMP data of part of the granitoids of the studied area indicate that the exposed Archaean terranes hide an older crust, as suggested by inherited zircon cores (3.05 Ga to 2.93 Ga). The magmatic age of the Crixás-Açu Gneisses (2817 ± 9 Ma) and the age of metakomatiites of the Crixás Belt (2825 ± 98 Ma; Arndt *et al.* 1989), added to their mutual field relationships leads to the interpretation that the gneisses are part of the M-type dome-and-keel structure evolution. The prior tonalitic intrusion underwent amphibolite facies metamorphism during the Archean, as deduced from the inferred metamorphic zircon (2772 ± 6 Ma). The oldest titanite population indicates that metamorphic cooling took place at *ca.* 2711 ± 34 Ma, and the youngest reflects a Palaeoproterozoic 2011 ± 15 Ma event materialized in the faint crosscutting fabric. The lack of resetting of the older population suggests that the youngest titanite grew below the minimum titanite U–Pb blocking temperature of 500°C (Cherniak 1993, Mezger *et al.* 1993, Mezger *et al.* 1991, Cliff and Cohen 1980). The example of the Crixás-Açu Gneisses is, on the other hand, a first known case where polymetamorphic rocks may contain titanite of more than one age if later events took place at lower temperatures.

Table 1 - Isotopic data from sample 98-38 (zircons), Crixás-Açú Gneiss, Caiamar Complex

Grain-spot	Zircon type	Location (c/r)	Statistical Group*	U (ppm)	$\frac{^{232}Th}{^{238}U}$	$f206$ (%)	$\frac{^{207}Pb^*}{^{206}Pb^*}$	$\frac{^{206}Pb^*}{^{238}U}$	$\frac{^{207}Pb^*}{^{235}U}$	$^{207}Pb/^{206}Pb$ Age (Ma)
14-1	2	c	1*	405	0,314	0,000	0,1989 ± 5	0,5081	13,935	2817 ± 4
22-1	2	r=c	1*	582	0,866	0,022	0,1987 ± 4	0,5025	13,770	2816 ± 3
27-1	1	c	1*	67	0,267	0,166	0,1990 ± 12	0,5339	14,651	2818 ± 10
27-2	1	c	1*	45	0,321	0,015	0,2017 ± 16	0,5569	15,490	2840 ± 13
29-1	3	c	2	277	0,517	0,036	0,1938 ± 6	0,5329	14,241	2775 ± 5
29-2	3	r=c	2	305	0,499	0,009	0,1932 ± 5	0,5293	14,102	2770 ± 4
09-1	2	r	-	689	0,059	0,034	0,1821 ± 4	0,3614	9,073	2672 ± 4
09-2	2	c	-	748	0,625	0,168	0,1792 ± 5	0,3271	8,084	2646 ± 4
09-3	2	r=c	-	439	0,641	0,217	0,1929 ± 6	0,4530	12,051	2767 ± 5
10-1	1	c	-	227	0,503	0,000	0,2299 ± 7	0,6006	19,035	3051 ± 5
10-2	1	r	-	676	0,147	0,140	0,1866 ± 4	0,3759	9,673	2713 ± 4
10-3	1	c	-	275	0,588	0,019	0,2243 ± 6	0,5911	18,284	3012 ± 4
11-1	2	r	-	439	0,551	0,078	0,1885 ± 6	0,4337	11,273	2729 ± 5
11-2	2	c	-	128	0,861	0,043	0,2165 ± 9	0,5955	17,780	2955 ± 7
11-3	2	c	-	125	0,936	0,000	0,2134 ± 9	0,5622	16,540	2931 ± 7
12-1	2	c	-	1442	0,218	0,022	0,1669 ± 3	0,2783	6,403	2527 ± 3
12-2	2	r	-	880	0,455	0,336	0,1836 ± 6	0,3229	8,176	2686 ± 5
13-1	2	r	-	398	0,261	0,088	0,1909 ± 5	0,4348	11,447	2750 ± 4
14-2	2	c	-	497	0,327	0,005	0,2007 ± 6	0,4883	13,509	2832 ± 5
16-1	2	c	-	341	0,308	0,000	0,1972 ± 5	0,4810	13,079	2803 ± 4
21-1	2	c	-	677	0,297	0,005	0,1968 ± 4	0,4693	12,736	2800 ± 3
23-1	2	r	-	788	0,488	0,108	0,1839 ± 4	0,3721	9,436	2689 ± 4
28-1	1	c	-	354	0,183	0,006	0,2183 ± 5	0,5494	16,537	2968 ± 4
28-2	1	c	-	226	0,040	0,038	0,2112 ± 6	0,5220	15,200	2915 ± 5
28-3	1	r=c	-	921	0,386	0,013	0,1737 ± 3	0,2924	7,002	2593 ± 3
29-3	3	c	-	332	0,703	0,010	0,1948 ± 5	0,4879	13,104	2783 ± 4
29-4	3	c	-	274	0,552	0,011	0,1898 ± 6	0,5051	13,217	2740 ± 5
30-1	2	r	-	462	0,321	0,013	0,1961 ± 4	0,4557	12,320	2794 ± 4
37-1	2	r	-	844	0,500	0,042	0,1765 ± 4	0,3246	7,901	2621 ± 3

* = used for age calculation.

Errors in column $^{207}Pb/^{206}Pb$ quoted as significant figures only. All errors ± 1σ. All data are 204 corrected.

Table 2 - Isotopic data from sample 98-77 (titanites), Crixás-Açú Gneiss, Caiamar Complex.

Grain-spot	Statistical Group*	U (ppm)	$\frac{^{232}Th}{^{238}U}$	$f206$ (%)	$\frac{^{207}Pb^*}{^{206}Pb^*}$	$\frac{^{206}Pb^*}{^{238}U}$	$\frac{^{207}Pb^*}{^{235}U}$	$^{207}Pb/^{206}Pb$ Age (M.y.)
01-1	3	45	0,392	2,855	0,1201 ± 33	0,3542	5,866	1958 ± 50
02-1	1*	96	0,235	2,254	0,1228 ± 23	0,3011	5,099	1998 ± 34
03-1	3	56	0,310	1,700	0,1267 ± 25	0,3557	6,213	2053 ± 35
04-1	3	80	0,135	1,541	0,1224 ± 20	0,3547	5,986	1992 ± 29
05-1	1*	52	0,319	1,222	0,1764 ± 23	0,4631	11,264	2619 ± 22
05-2	1*	97	0,264	1,458	0,1349 ± 20	0,3813	7,092	2163 ± 25
07-1	2*	80	0,111	0,585	0,1870 ± 13	0,5065	13,061	2716 ± 11
07-2	2*	93	0,116	0,606	0,1858 ± 13	0,5199	13,316	2705 ± 12
08-1	3	52	0,232	1,934	0,1242 ± 26	0,3603	6,169	2017 ± 37
09-1	3	42	0,412	2,772	0,1224 ± 37	0,3546	5,987	1992 ± 53
10-1	3	91	0,130	1,472	0,1224 ± 17	0,3583	6,049	1992 ± 25
11-1	3	27	0,372	3,195	0,1266 ± 47	0,3659	6,387	2051 ± 65
11-2	1*	31	0,326	7,309	0,1369 ± 68	0,3650	6,889	2188 ± 86
12-1	3	90	0,221	1,336	0,1219 ± 17	0,3656	6,143	1984 ± 24
13-1	2*	26	0,166	2,020	0,1873 ± 36	0,5200	13,427	2718 ± 31
13-2	1*	32	0,076	2,468	0,1751 ± 36	0,4975	12,011	2607 ± 35
21-1	3	36	0,517	3,188	0,1254 ± 43	0,3554	6,148	2035 ± 61
28-1	3	89	0,192	2,504	0,1241 ± 24	0,3644	6,235	2016 ± 35
29-1	3	51	0,243	2,134	0,1246 ± 33	0,3609	6,197	2023 ± 46
31-1	1*	73	0,579	4,134	0,1164 ± 36	0,3237	5,194	1901 ± 56
32-1	3	31	0,410	3,822	0,1202 ± 51	0,3579	5,929	1959 ± 76
35-1	3	39	0,458	3,077	0,1227 ± 41	0,3624	6,129	1995 ± 60
39-1	3	143	0,115	0,829	0,1254 ± 12	0,3624	6,267	2035 ± 17
40-1	3	95	0,278	1,787	0,1202 ± 21	0,3438	5,698	1959 ± 31
42-1	3	102	0,330	1,146	0,1241 ± 16	0,3544	6,063	2016 ± 24
43-1	1*	33	0,106	3,203	0,1408 ± 44	0,3610	7,006	2237 ± 54
44-1	3	46	0,317	2,586	0,1219 ± 35	0,3605	6,060	1984 ± 51
45-1	3	137	0,488	0,923	0,1257 ± 14	0,3519	6,100	2039 ± 20
46-1	1*	93	1,065	0,885	0,1785 ± 14	0,4892	12,042	2639 ± 13
46-2	1*	55	0,775	0,858	0,1830 ± 19	0,4928	12,436	2680 ± 17
47-1	3	98	0,122	1,558	0,1234 ± 23	0,3483	5,925	2006 ± 33

* = used for age calculation.

Errors in column $^{207}Pb/^{206}Pb$ quoted as significant figures only.

All errors ± 1σ.

All data are 204 corrected.

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